

Multi-Rate Flowing Wellbore Electric Conductivity Logging Method

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Abstract

The flowing wellbore electric conductivity logging method involves the replacement of wellbore water by de-ionized or constant-salinity water, followed by constant pumping with rate Q , during which a series of fluid electric conductivity logs are taken. The logs can be analyzed to identify depth locations of inflow, and evaluate the transmissivity and electric conductivity (salinity) of the fluid at each inflow point. The present paper proposes the use of the method with two or more pumping rates. In particular it is recommended that the method be applied three times with pumping rates Q , $Q/2$, and $2Q$. Then a combined analysis of the multi-rate data allows an efficient means of determining transmissivity and salinity values of all inflow points along a well with a confidence measure, as well as their inherent or “far-field” pressure heads. The method is illustrated by a practical example.

Introduction

In the study of flow and transport in the subsurface, knowledge of flow zones and their hydraulic properties is essential. Often such knowledge is obtained through testing in boreholes penetrating into the ground for tens to thousands of meters. The objective of the tests is to determine the flow transmissivity T as a function of depth. Since the subsurface is typically heterogeneous, the transmissivity is expected to vary with depth, and the variability will be a function of spatial resolution along the borehole — the finer the resolution, the stronger the variability. For the particular case of fractured rock, flow will be localized to a number of discrete depth levels, corresponding to positions where the borehole intercepts hydraulically conductive fractures. In this paper, these locations along the borehole are designated as feed points, or feed zones if flow occurs through a thick permeable layer penetrated by the borehole.

In addition to having individual T values, and feed point or zone is also characterized by its salinity C and its inherent “far-field” pressure head h , which is the equilibrium pressure head when the flow zone is isolated for a time period. In the present study, the chemical composition of the fluid flowing from the conductive rock zones into the borehole is not directly measured. Instead, the composition is inferred by the fluid electrical conductivity FEC, which can be simply related to salinity or equivalent NaCl concentration C in g/L by (Shedlovsky and Shedlovsky, 1971):

$$FEC (20^\circ) = 1870 C - 40 C^2. \quad (1)$$

Where FEC is assumed to be measured at 20°C. For FEC measured at another temperature T in °C, Schlumberger (1984) provides a conversion:

$$FEC(20^\circ) = \frac{FEC(T)}{1 + S(T - 20^\circ)}, \quad (2)$$

where S is a parameter with value 0.024. Often salinity increases with depth; however, it may also vary more erratically, depending on the flow paths that lead to a particular feed point. It has been noted in the field that two neighboring inflow points can have salinities that differ by as much as a factor of 5–10 (Tsang, et al., 1990).

The inherent hydraulic heads of multiple feed points or zones in a borehole would not vary with depth if the medium were homogeneous and well connected to a common land-surface level. However, the subsurface is normally heterogeneous and, in the case of a fractured medium, it is often hydraulically compartmentalized into discrete regions each having a slightly different hydraulic head. These head differences at feed points along a wellbore cause what is known as wellbore internal flow; i.e., when the well is shut-in with no pumping out of or into the well, water flows into the well from points with higher pressure heads and exits at points with lower pressure heads.

Making the measurements of T_i , C_i , and h_i for each feed point i along the wellbore is a time consuming exercise. One typical method is to install a double packer across a feed point and then conduct a pumping test in the packed-off interval by measuring the pressure drawdown for the particular pumping rate applied. An analysis of such data will yield T_i . Similarly, C_i can be obtained by measuring fluid FEC value or C_i after sufficient pumping is done to ensure that the formation fluid has fully replaced the initial fluid in the tubing and the packer interval. The inherent pressure head h_i for the inflow point can be obtained by monitoring the pressure in the packer interval with no pumping for an extended time until the pressure equilibrates with the inherent, far-field pressure in the feed zone or conductive fracture. These measurements have to

be conducted one feed point at a time. For a 500-m well in fractured rock, for example, there could be more than 20 inflow points, and it is quite laborious and time consuming to perform these tests one by one for each point.

The flowing wellbore electric-conductivity logging method (Tsang, et al., 1990) was proposed as a method that can measure T_i effectively, and has been shown to take much less time than the packer test method. The method also yields information on C_i . It has been applied extensively by Marschall, Vomvoris and co-worker's (1995) in deep wells down to 1500 m or more, and by Pedler, et al. (1992), Evans, et al. (1992), and Bauer and LoCoco (1996) in shallower wells down to 100–500 m. Improvements to analysis methods were made by Evans (1995). More recently, Doughty and Tsang (2002) further improved the analysis method, on the one hand to allow analysis of natural regional flow, and, on the other, to provide distinctive signatures to help with log analysis.

This paper builds on the earlier studies and introduces the concept of combined analysis of logs with two or more pumping rates. It is shown that such multi-rate logging will provide results not only for T_i and C_i , and but also for h_i . To be able to obtain these parameters for all feed points or zones along a wellbore with two or three sets of measurements represents a powerful and potentially very useful tool in the study of flow and transport in heterogeneous media.

The following section summarizes the basic flowing wellbore electric conductivity logging method. Then the concept and analysis of the multiple-rate fluid logging method are presented. Based on actual field data, a set of synthetic logs with multiple rates is generated and analyzed with the new technique to demonstrate the new approach. The paper concludes with some general remarks.

Flowing Wellbore Electric Conductivity Logging Method

The basic discussion of the method may be found in Tsang et al. (1990). In this method, the wellbore water is first replaced by de-ionized water or, alternatively, by water of a constant salinity distinctly different from that of the formation water. This is done by passing the de-ionized water down a tube to the bottom of the borehole at a given rate, while simultaneously pumping from the top of the well at the same rate. Next, the well is shut in and the tube is removed. Then the well is pumped from the top at a constant low flow rate Q (e.g., a few liters per minute), while an electric conductivity probe is lowered into the borehole to scan the fluid electric conductivity FEC as a function of depth. With constant pumping conditions, a series of five or six logs are typically obtained over a few-hour to one- or two-day period. At depth locations z_i where water enters the borehole (the feed points), the logs display peaks. Thus, these peak locations give the depths of the inflow points or zones (with typical resolution of about 10 cm). These peaks grow with time and are skewed in the direction of water flow. The area under a peak is proportional to $q_i C_i$ (where q_i is inflow rate at a particular feed point) and the skewness of the peak depends on $\sum q_i$ over the inflow points below (or upstream of) the point in question. Thus, by analyzing these logs, it is possible to obtain the flow rate and salinity of groundwater inflow from each individual feed point. The method is more accurate than spinner flow meters and much more efficient than packer tests (Tsang et al., 1990).

Figure 1 shows two typical FEC logs. Figure 1a is from measurements in an 80-m well labeled 'W00' at the Raymond field site in California, where a comprehensive study of well test methods to characterize fracture hydrology was conducted (Karasaki et al., 2000). The logs (dashed lines) were taken over a period of about one hour after the well water was replaced by de-ionized water and pumping was initiated. The pumping rate from the well was at 9 L/min.

Five inflow points were identified over the 80-m depth. The solid lines are model results discussed below in the section on the example application. Figure 1b shows the FEC logs in a deeper well in northern Switzerland (Tsang, et al., 1990). Five logs were taken along a depth interval from 700 to 1650 m over a two-day period. Nine inflow points were identified.

The numerical model BORE (Hale and Tsang, 1988; Tsang, et al., 1990) and the recently enhanced version BORE II (Doughty and Tsang, 2000) calculate FEC logs, given a set of inflow locations z_i , feed point flow rates q_i , and salinities C_i . The BORE II code solves the one-dimensional advection-diffusion equation for flow and transport along the well using the finite-difference method, assuming (a) feed points to act as mass sources or sinks, (b) fluid flow is steady, and (c) complete mixing occurs across the wellbore cross-sectional area. BORE II is typically employed in a trial-and-error inverse process to obtain feed point parameters by comparing calculated FEC profiles to observed FEC logs.

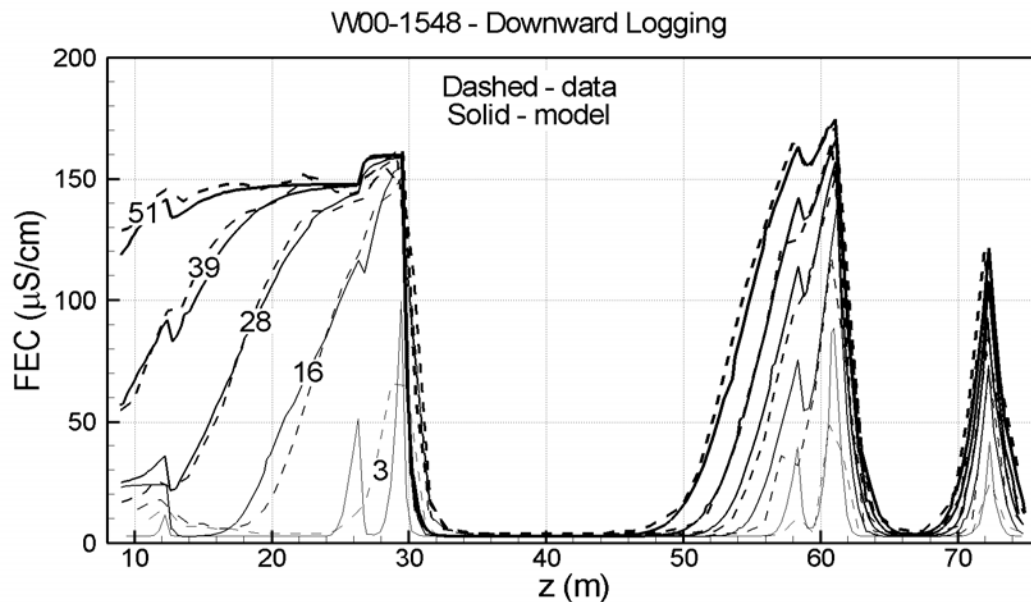


Figure 1a. FEC logs from the Raymond field site in California (Karasaki et al., 2000). The labels on the curves identify elapsed time in minutes from the start of logging.

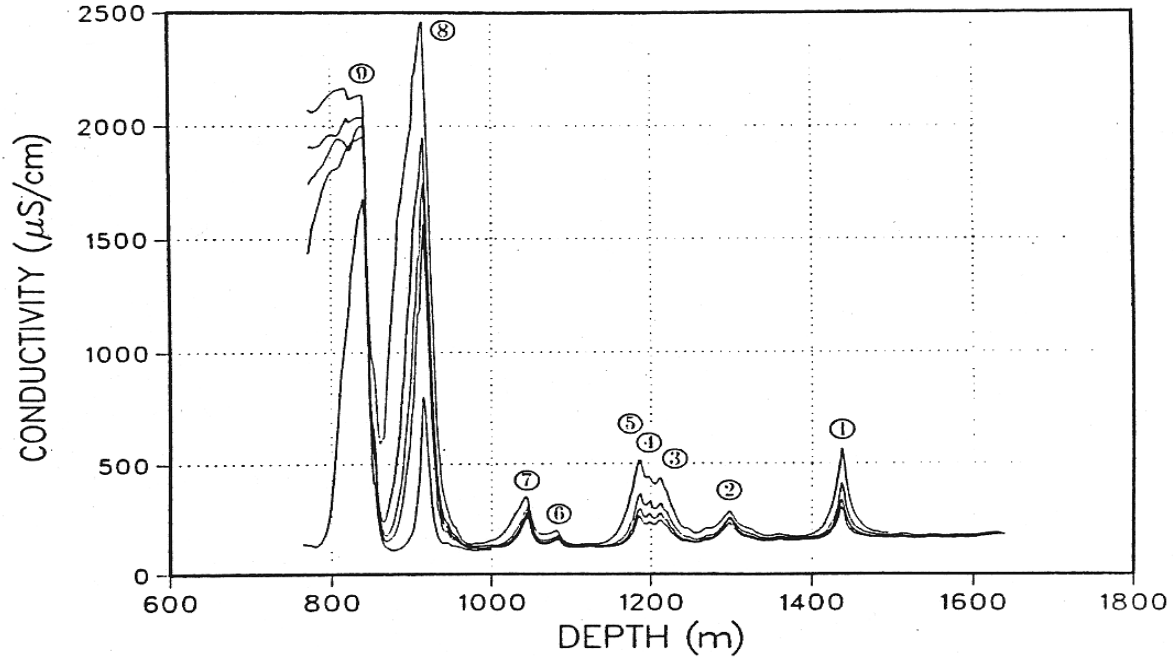


Figure 1b. FEC for the full logged 770 to 1610 m section of the 1690 m Leuggern borehole in northern Switzerland (Tsang et al., 1990). The circled numbers identify feed points.

Multi-rate Logging Method

To date, the flowing FEC logging method has been applied to the analysis of a set of logs with one constant pumping rate Q from the well. The values of z_i , q_i and C_i are obtained through the use of the BORE or BORE II code. Then the transmissivity of each inflow point, T_i , can be calculated from q_i and the pressure-head drawdown in the wellbore Δh_{wb} .

We show below that by simultaneously analyzing one or more additional sets of FEC logs with different Q 's, not only T_i and C_i can be determined with better confidence, but the inherent pressure heads of each inflow point, h_i can also be obtained. In principle, two sets of logs with two different Q 's are enough. However, three sets at three different Q values are recommended to provide additional internal checking of the results.

Let us consider a wellbore containing N inflow points. The strength of the i th feed point is q_i and $\sum q_i = Q$. By convention, inflow points have positive q_i and outflow points have negative q_i . Upflow from below the studied interval can be absent (e.g., the lower end of the interval is at the well bottom or at an inflated packer), or represented by a special feed point at the lower end. For each feed point, q_i and concentration C_i are assumed to be constant in time. The strength of a feed point q_i is related to its hydraulic transmissivity T_i^* , the inherent “far-field” pressure head h_i at a distance r_i away from the wellbore, and the pressure head h_{wb} at the wellbore radius r , through Darcy’s law. Assuming steady radial flow into the wellbore,

$$q_i = \frac{2\pi T_i^* (h_i - h_{wb})}{\ln(r_i / r)} = T_i (h_i - h_{wb}), \quad (3)$$

where T_i represents an effective hydraulic transmissivity, into which the constant factors involving radial distances have been lumped. We assume that the hydraulic transmissivity within the wellbore itself is much greater than that of any inflow zone, so that h_{wb} is constant over the wellbore interval being studied. Since $\sum q_i = Q$, we can write

$$Q = \sum T_i (h_i - h_{wb}). \quad (4)$$

If we now alter the pumping rate from Q to Q' , T_i and h_i remain unchanged but h_{wb} becomes h_{wb}' , and

$$q_i' = T_i (h_i - h_{wb}') \quad (5)$$

$$Q' = \sum T_i (h_i - h_{wb}'). \quad (6)$$

Taking the difference between Equations (3) and (5) and between Equations (4) and (6) give, respectively,

$$\Delta q_i = T_i(h_{wb} - h_{wb}') . \quad (7)$$

$$\Delta Q = T_{tot}(h_{wb} - h_{wb}') \quad (8)$$

where $\Delta q_i = q_i' - q_i$, $\Delta Q = Q' - Q$, and $T_{tot} = \Sigma T_i$.

Equations (7) and (8) can be combined to yield

$$\frac{T_i}{T_{tot}} = \frac{\Delta q_i}{\Delta Q} \quad (9)$$

which is the fundamental relationship between the change in feed-point strength Δq_i and the change in pumping rate ΔQ . Note that Δq_i is directly proportional to T_i , and thus the feed points with larger hydraulic transmissivity show greater changes in strength when Q is modified. In particular, if the j th feed point has a much larger hydraulic transmissivity than all the others ($T_j \approx T_{tot}$), then $\Delta q_j \approx \Delta Q$ and all the other feed-point strengths will not change much. This situation might arise if the well intercepts an extensive feed zone that has not been excluded from the logging section by packers.

Equation (7) can be used to relate T_i to a particular T_j at feed point j

$$\frac{T_i}{T_j} = \frac{\Delta q_i}{\Delta q_j} . \quad (10)$$

Furthermore, when we divide Equation (7) by Equation (3) we obtain

$$\frac{q_i}{\Delta q_i} = \frac{h_i - h_{wb}}{h_{wb} - h_{wb}'} , \quad (11)$$

so that

$$\frac{h_i - h_{wb}}{h_j - h_{wb}} = \frac{q_i / \Delta q_i}{q_j / \Delta q_j} \quad (12)$$

This means that if we know the T_j and h_j for a particular feed point (e.g., by means of a normal pressure test using a double-packer across it), we can use the analysis results q_i and Δq_i of two-rate flowing FEC logs, to obtain T_i and h_i for all the other feed points by means of Equations (10) and (12) without having to make double-packer pressure tests for the feed points one by one. Note that Equations (10) and (12) consider only two feed points at a time, and are not depended on inaccuracies in measurements of the other inflow points and in the total quantities Q and T_{tot} .

There are several special cases of Equation (9) that are of interest. If all the T_i 's are the same, then $T_i = T_{tot}/N$, and Equation (9) simplifies to

$$\Delta q_i = \frac{\Delta Q}{N}, \quad (13)$$

where N is the number of feed points. In this case, when Q is modified, all feed-point strengths change by the same amount.

On the other hand, if the h_i 's are all the same, then combining Equations (3) and (4) yields

$$\frac{q_i}{Q} = \frac{T_i}{T_{tot}}. \quad (14)$$

Then, substituting for T_i/T_{tot} using Equation (9) gives

$$\frac{q_i}{Q} = \frac{\Delta q_i}{\Delta Q}. \quad (15)$$

Note that when all the h_i 's are the same, feed points must be either all inflow points or all outflow points. In this case, when Q is modified, the relative change of each feed point $\Delta q_i/q_i$ is the same and is equal to the relative change of Q , i.e.,

$$\frac{\Delta q_i}{q_i} = \frac{\Delta Q}{Q} . \quad (16)$$

Conversely, increasing or decreasing Q by a factor of two and finding q_i not changed by the same factor of two is a clear indication that the h_i 's are not the same.

Finally, if all the T_i 's are the same and all the h_i 's are the same, then according to Equation (3), all the q_i 's must be the same. Thus, $q_i = Q/N$, and Equations (13) and (16) become equivalent.

The above development provides a practical way to analyze flowing FEC logs when two sets of FEC logs with Q and $Q + \Delta Q$ are available. Let us assume that we apply the BORE II code to each set and obtained the q_i 's and C_i 's. Then Equation (9) can be used to obtain T_i/T_{tot} . Further, we can rewrite Equation (4) as

$$Q = \sum T_i(h_i - h_{wb}) = T_{tot}(h_{avg} - h_{wb}) , \quad (17)$$

where h_{avg} , defined as

$$h_{avg} = \sum(T_i h_i)/T_{tot} , \quad (18)$$

is the hydraulic-transmissivity weighted average of the inherent pressure heads. Note that h_{avg} can be measured by a pressure probe in the wellbore when it is shut-in, because with $Q = 0$, Equation (17) gives $h_{wb} = h_{avg}$.

Taking the ratio of Equation (3) and Equation (17), then rearranging, yields a convenient measure of feed point inherent pressure head h_i

$$\frac{(h_i - h_{avg})}{(h_{avg} - h_{wb})} = \frac{q_i/Q}{T_i/T_{tot}} - 1. \quad (19)$$

The group on the left hand side provides a dimensionless measure of the departure of feed point inherent pressure head from h_{avg} . Note that the denominator in the left hand side of Equation (16) is nothing other than the pressure head draw-down in the well when it is pumped at rate Q , and this can be measured directly.

In summary, Equations (9) and (19) provide the fundamental formulas that enable the use of quantities provided by a combined BORE II analysis of multi-rate logging data to calculate T_i/T_{tot} and $(h_i - h_{avg})/(h_{avg} - h_{wb})$, where h_{wb} is the wellbore pressure head measured for pumping rate Q . To conduct the analysis, two sets of FEC logs at two pumping rates (at Q and $2Q$, for example) are all that is needed. However, if we have three sets of logs for three pumping rates, Q_1 , Q_2 , and Q_3 , then we can obtain three sets of results by analyzing three combinations of data (Q_1 and Q_2), (Q_2 and Q_3), and (Q_3 and Q_1). This provides internal checking, reduces the impact of measurement errors, and gives a confidence measure in the analysis results.

For the particular case that T_j and h_j at one particular feed point j are known, through a packer test conducted either just before or after the multi-rate flowing FEC logging procedure, Equations (10) and (12) can be used to obtain T_i and h_i of all the other feed points along the borehole.

Example of Application

Generation of a Synthetic Case

A synthetic case is generated using field data shown in Figure 1a. The five FEC logs were analyzed with the BORE II code, and six inflow locations were identified with q_i and C_i determined for each feed point: the results are shown in Table 1 and Figure 2(a) and (b). The BORE II model for the 80 m deep well has 180 cells, resulting in about 0.4 m spatial resolution. The calculated FEC profiles are shown in Figure 1a as solid lines and they match approximately the field data. To obtain T_i/T_{tot} from q_i requires an assumption for h_i . Commonly it is assumed that all the h_i 's are the same and equal to h_{avg} . Then T_i/T_{tot} values are directly proportional to $q_i/\Sigma q_i$ [Equation (14)]. These T_i/T_{tot} quantities are shown in Table 1 and also as solid columns in Figure 2(c). However, there are cases for which all the h_i 's may not be the same, then T_i/T_{tot} will be different from those shown in the fourth row of Table 1.

Table 1. Parameters of example application.

	z_i (m)	12	26.1	29.2	44	58.1	61	72
Fit to field data using BORE II	C_i (g/L)	0.149	0.072	0.610	—	0.12	0.12	0.525
	q_i (L/min)	0.715	4.000	2.140	—	0.660	1.400	0.100
Constant $h_i = h_{avg}$ [use Eq. (14)]	T_i/T_{tot} (constant h_i)	0.077	0.431	0.260	—	0.071	0.151	0.011
Variable h_i (set externally)	$(h_i - h_{avg})/(h_{avg} - h_{wb})$	-0.762	0.987	0.987	-1.513	-0.013	-0.013	0.487
Assume variable h_i from row above [use Eq. (19)]	T_i/T_{tot} (variable h_i)	0.336	0.224	0.135	0.065	0.074	0.158	0.070

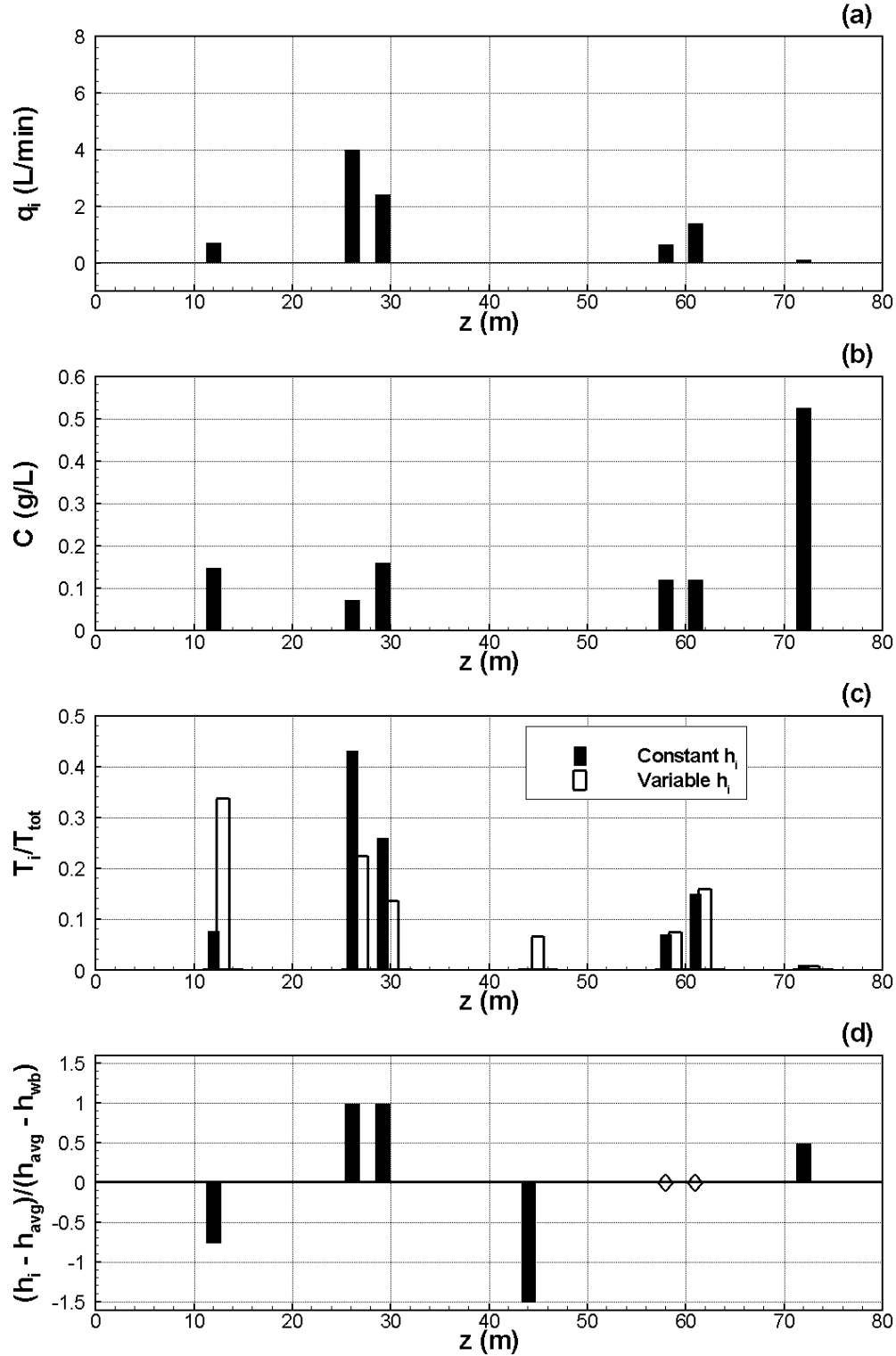


Figure 2. Parameters of example application: (a) and (b) show the q_i and C_i values, respectively, obtained using BORE II to fit Raymond field data; (c) shows T_i/T_{tot} values obtained from (a) for two alternative assumptions about inherent pressure heads h_i , constant or variable; and (d) shows the variable h_i values assumed for the synthetic case (bars and diamond symbols).

Now, to study this effect, let the hydraulic heads h_i be set different from each other as specified in the fifth row of Table 1 and shown in Figure 2(d). Here we have imposed pressure head h_i slightly smaller than h_{avg} for the two feed points $z = 58.1$ and 61 m, and significantly smaller than h_{avg} at $z = 12$ m. Further, we added a feed point at $z = 44$ m, with a sufficiently small h_i that the initial pumping rate Q would not cause a low enough pressure head in the well h_{wb} to induce inflow into the well (i.e., $h_i < h_{wb}$). Given these h_i values, new T_i/T_{tot} can be calculated using Equation (19) and they are shown in the lowest row in Table 1 and as open columns in Figure 2(c). The T_i/T_{tot} for the new feed point at $z = 44$ meters with very low h_i cannot be calculated from field data, since q_i at this feed point is negative (i.e., $h_i - h_{wb}$ is negative corresponding to outflow from the well). Hence an arbitrary value of $T_i/T_{tot} = 0.065$ is assigned to it.

Note that Figure 2(c) shows the errors introduced in T_i/T_{tot} when calculated assuming constant pressure heads h_i for all feed points, if in fact the real h_i are as shown in Figure 2(d).

The multi-rate flowing FEC logging method provides a means to determine the inherent pressure heads of the feed points and their transmissivities as discussed in the last section. To test the method, a synthetic data set is constructed based on parameters, C_i , T_i/T_{tot} , and $(h_i - h_{avg})/(h_{avg} - h_{wb})$, (where h_{wb} corresponds to Q used in the field data). The parameters are shown in Table 1, rows 2, 5, and 6. Three synthetic FEC logs were generated by forward calculations using the BORE II code for Q , $2Q$ and $Q/2$. They are shown in Figure 3. Random errors have been introduced into the synthetic data so that they better reflect the noisy character of real field data. These are the logs to be analyzed by the multi-rate log analysis method.

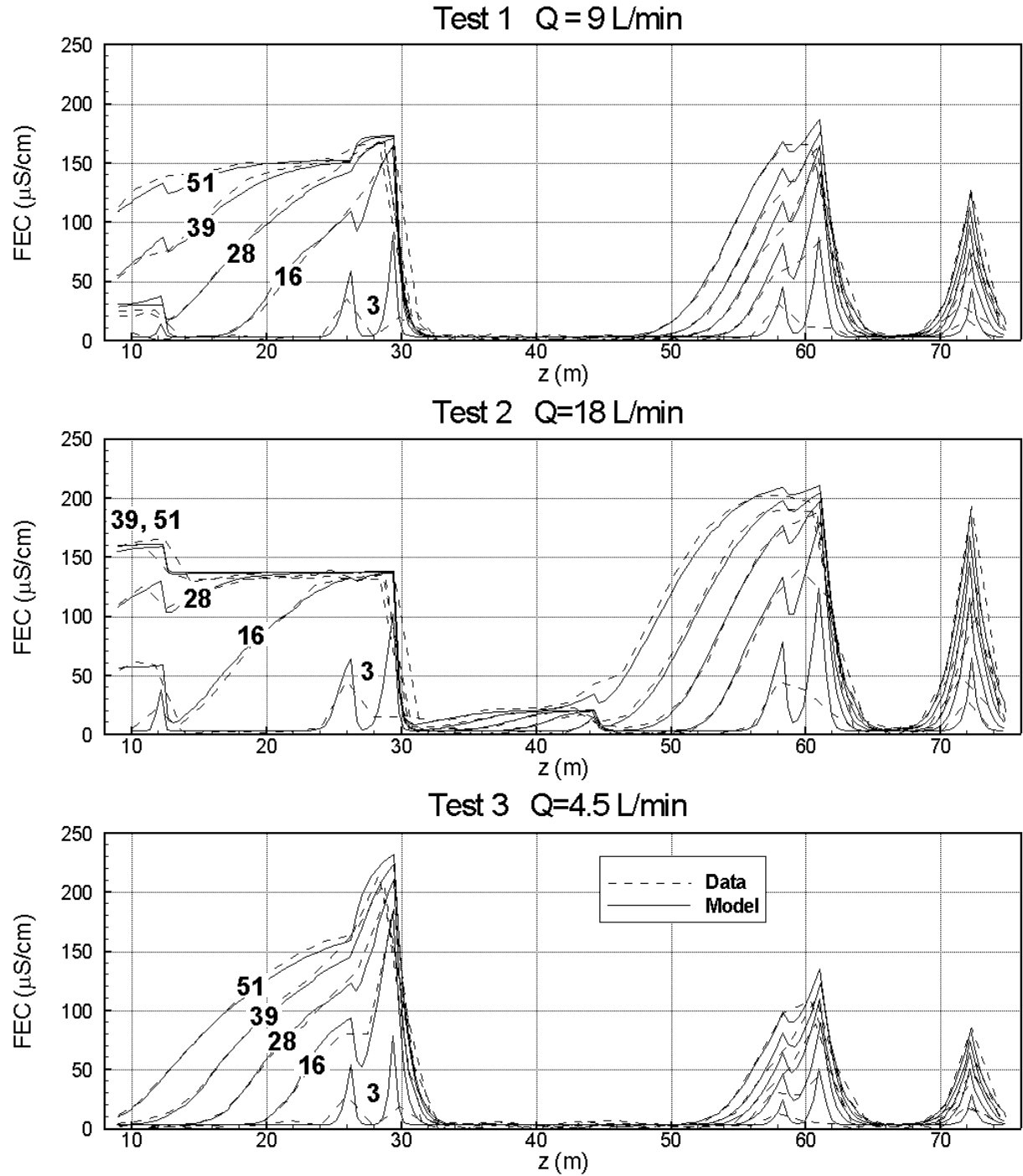


Figure 3. Synthetic FEC data for three pumping rates (data) and corresponding BORE II match (model). The Test 1 Q corresponds to what was used at the Raymond field site. Curve labels show elapsed time in minutes since pumping began.

Multi-rate Log Analysis and Results

Using the standard fluid conductivity logging methods, the three logs in Figure 3 were analyzed using the BORE II code, with the constraint that the set of C_i values for the three logs must be the same. The resulting q_i 's for the three pumping ratios $Q/2$, Q and $2Q$ are then obtained and are shown in Figure 4(a). If the h_i had been the same for all feed points, the q_i 's should be proportional to Q . The fact that they are not indicates that the h_i 's are not the same.

With the three sets of q_i values for the three different pumping rates, we can take two sets at a time and use Equation (9) to calculate three sets of T_i/T_{tot} values. The results are as shown in Figure 4(c). The degree of agreement among the three sets of results gives a confidence measure of how well the transmissivity at the different feed points are determined.

Then, Equation (19) can be used to calculate the inherent pressure heads associated with the feed points. Using results for pumping rates Q and $Q/2$, and then for Q and $2Q$, $(h_i - h_{avg})/(h_{avg} - h_{wb})$ are calculated and shown in Figure 4(d), where h_{wb} corresponds to the wellbore pressure for pumping rate Q . Again the degree of their agreement with each other indicates a confidence level of these results. A comparison of Figure 4(d) and the input Figure 2(d) shows the input parameters are well reproduced and the “degree of agreement” shown in Figure 4(d) is a good measure of the degree to which Figure 2(d) is reproduced.

Now, since the h_i 's are different, one would expect internal flow within the wellbore when the well is shut-in ($Q = 0$). Flow will enter the well from feed points with high h_i and exit through feed points with low h_i . If an FEC log is taken after the wellbore is replaced with de-ionized water, but before pumping starts, the logs will register the internal flow conditions.

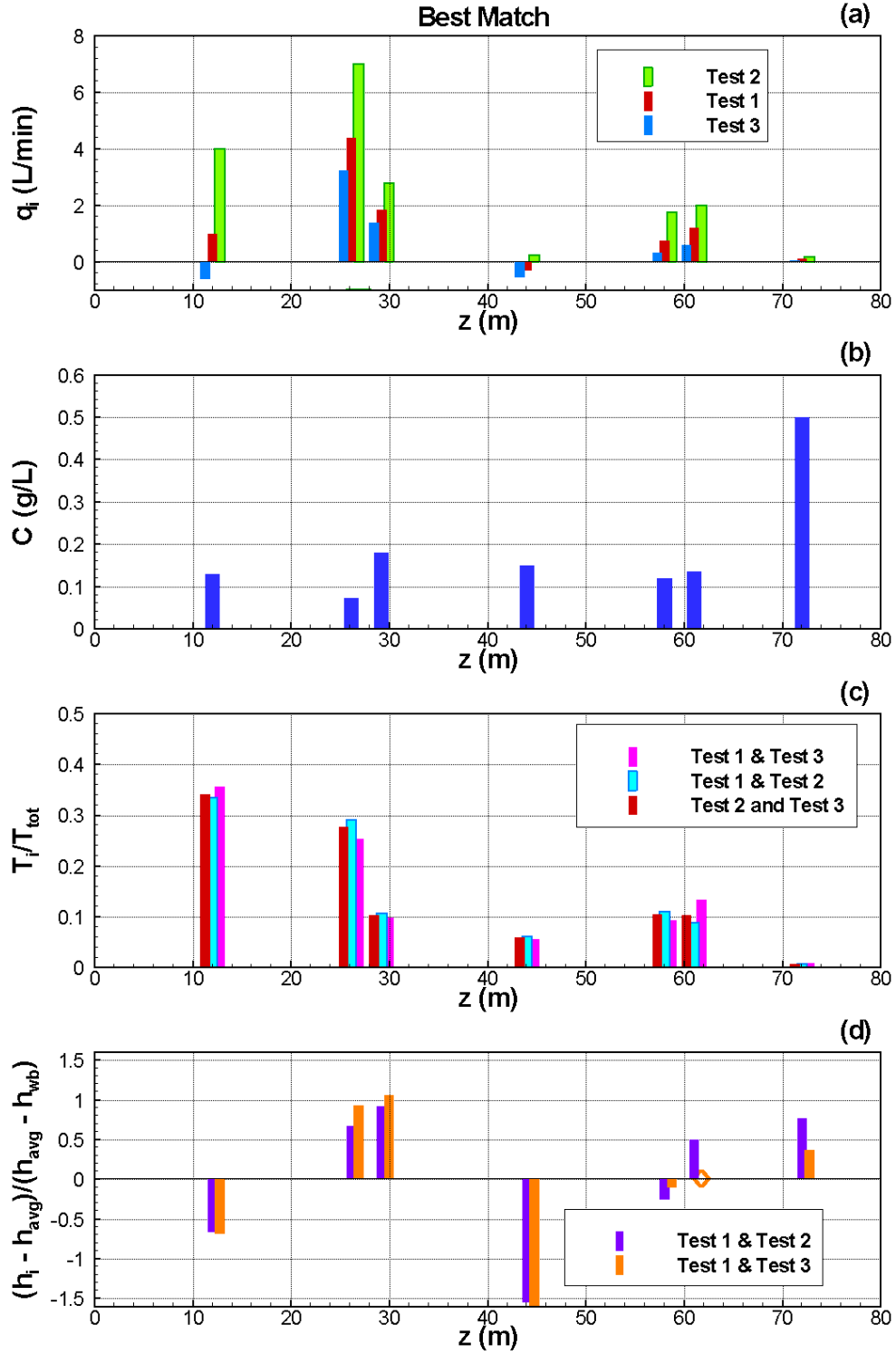


Figure 4. Results of BORE II multi-rate logging analysis: (a) feed point strengths for each of the three tests; (b) feed point salinities (constrained to be same for all three tests); (c) feed point T_i/T_{tot} values obtained by analyzing three pairs of tests; (d) feed point inherent pressure heads obtained by analyzing the two pairs of tests that include Test 1 (i.e., h_{wb} corresponds to Test 1).

With the results from Figure 4(b)-(d), FEC logs are calculated assuming $Q = 0$ for a series of times after the wellbore fluid replacement. The results are shown in Figure 5, in which peaks are seen at feed points where $h_i > h_{avg}$, as one would expect, and these grow with time. In this figure the broken lines labeled ‘Data’ are obtained by forward BORE II calculations using parameters in Table 1 (rows 1–3, 6) and the solid lines labeled ‘Model’ are calculated using parameter values obtained from the multi-rate FEC log analysis (Figure 4).

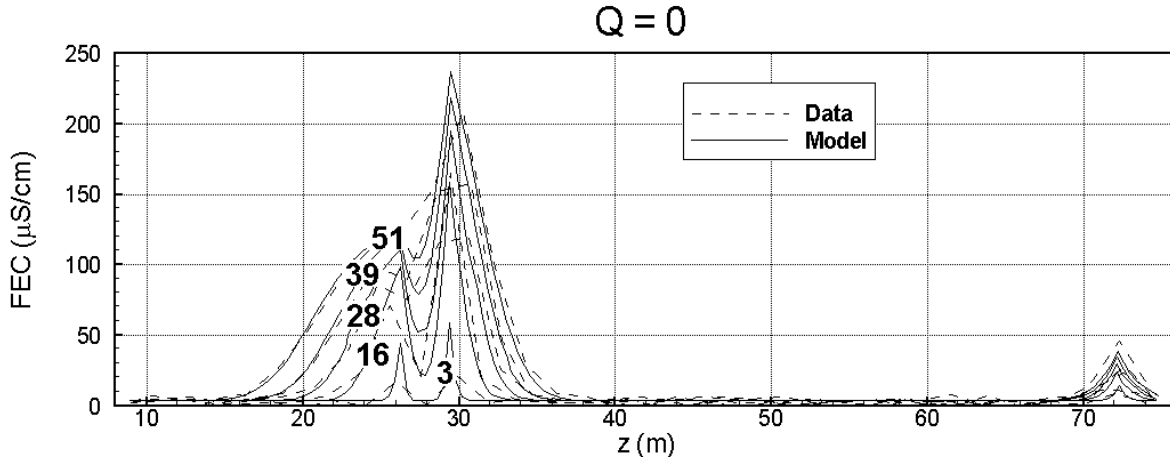


Figure 5. Synthetic FEC data for zero pumping rate (data) and corresponding BORE II match (model). Curve labels show elapsed time in minutes since the well was shut in.

Concluding Remarks

The paper presents a powerful method that efficiently determines values of T_i/T_{tot} , C_i and $(h_i - h_{avg})/(h_{avg} - h_{wb})$ of hydraulically conductive features along a wellbore. The method can be applied to a well with depths from about 10 to 2000 meters, and involves only three sets of logging runs over a very short time compared with the time required by other methods.

By conducting a conventional well test analysis over the whole length of the well, T_{tot} and h_{wb} can be obtained. Then, T_i , C_i and h_i can be individually determined. Alternatively, if, for a

particular feed point j , T_j , C_j and h_j are measured by a double-packer pressure test and sampling, these quantities for all other feed points can also be determined. Note that the C_i values determined by the multi-rate flowing FEC logging method are inherent to the feed point characteristics and not affected by dilution, which is often associated with other measurement methods. Also the determination of h_i is quite accurate, since it is scaled by $(h_{avg} - h_{wb})$, which in some cases may be only a few meters. Thus the accuracy of h_i determination could be a fraction of a meter.

Results of C_i can be independently verified against measurements of water samples taken from the well at different depths. Results of h_i can also be independently verified using FEC logging results with $Q = 0$. Thus, an FEC log can be taken at a time after borehole water replacement and before pumping start for the regular flowing FEC log measurements. Such $Q = 0$ logs can be used to verify predicted results, as shown in Figure 5.

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